Interferometry of Efimov states in thermal gases by modulated magnetic fields

Critical stability of few-body quantum systems
ECT*, October 23rd –27th

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MAX-PLANCK-GESELLSCHAFT

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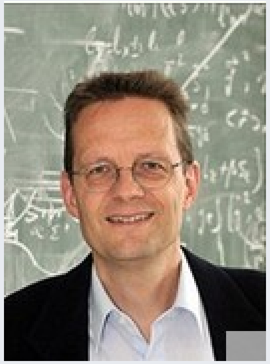
Brief Outline

- Introduction
  - Wiggle spectroscopy
  - Dynamics in Efimov states
- Ramsey-type interferometry of Efimov states in thermal gases
  - A dynamical protocol addressing the lifetime and binding energies of trimers

In collaboration with



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Introduction: Two-body physics

- Low energy limit: the de Broglie wavelength is the dominant length scale
  - The true interatomic potential is described by a single parameter, i.e. scattering length
  - The magnitude and sign of scattering length dictate the effective interaction between atoms
- Feshbach resonances: A mechanism that allows to tune the scattering length with magnetic fields

$$a(B) = a_{bg}\left(1 - \frac{\Delta}{B - B_0}\right)$$

- If $a > 0$ near Feshbach resonances permit the formation of "Feshbach Molecules"

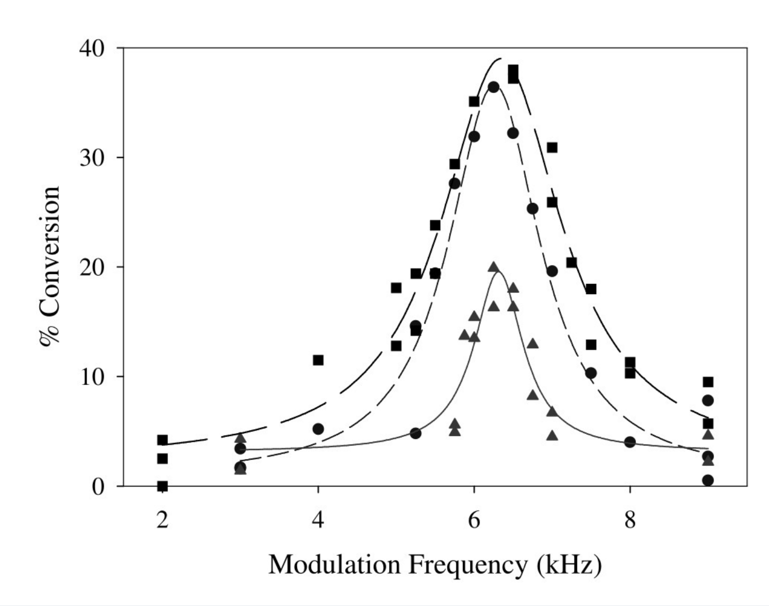
$$E_{bind} = -\frac{\hbar^2}{ma^2}$$

Ultracold gases – An introduction

- Wiggle spectroscopy in ultracold atoms
  - Using a radio-frequency oscillating magnetic field

$$B(t) = B + b\cos(\omega t)$$

  - Used to measure molecular binding energies and other properties of alkali atoms

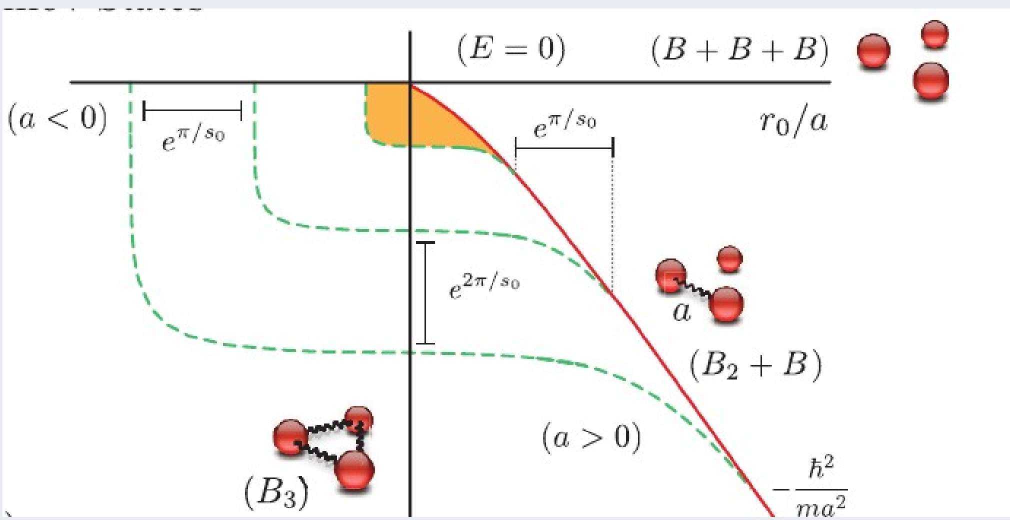


S. T. Thompson, E. Hodby, and C. E. Wieman, PRL. 95, 190404 (2005)
C. Weber et al., PRA 78, 061601(R) (2008)
A. D. Lange et al. PRA 79, 013622 (2009)
O. Machtey, Z. Shotan, N. Gross, and L. Khaykovich, PRL 108, 210406 (2012)
P. Dyke, S.E. Pollack, and R.G. Hulet, PRA 88, 023625 (2013)

Introduction: Beyond two-body physics

- An exotic class of triatomic molecules → Efimov states
  - Three identical bosons interact with short range interactions
  - The two-body subsystems are unbound, i.e. $a \to -\infty$
  - Their binding energies form an infinite geometric progression

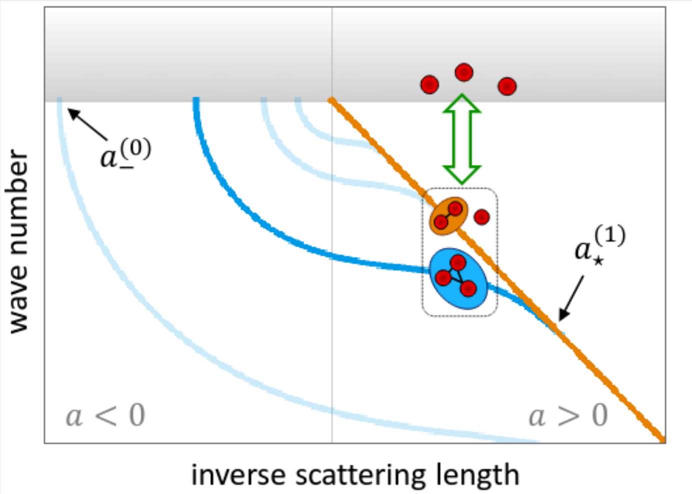
V. Efimov, Sov. J. Nucl. Phys. 12, 589-595 (1971)
V. Efimov, Physics Letters B, 33, 563-564 (1970)



- 1^{st} Experimental observation: Kraemer et al., nature 440, 16 (2006)
  - At $E \sim 0$ and $a < 0$ the Efimov states emerge as resonances in three-body recombination processes
  - Not possible at $a > 0$

Motivation: Dynamics in few-body systems

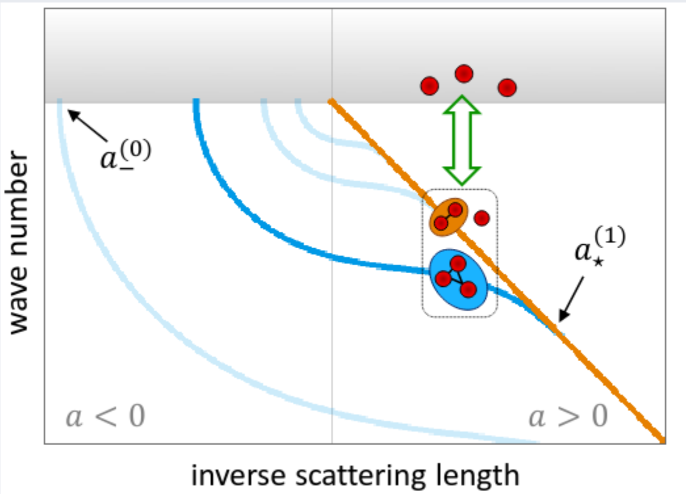
Are there alternative ways to probe Efimov states?

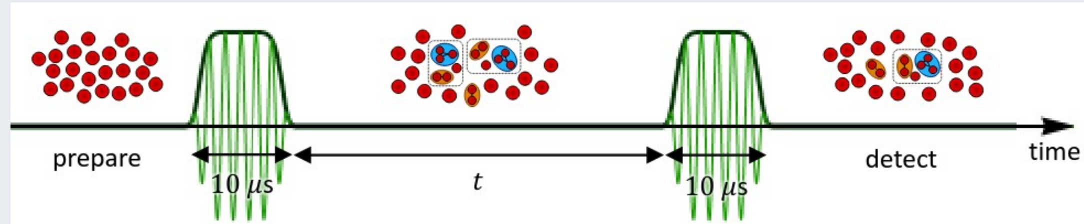


- Dynamical protocols probe the problematic region of $a > 0$
  - Gas of Rb atoms: Quenching a to unitarity followed by a sweep to weak interactions Catherine E. Klauss et al., PRL 119, 143401 (2017)
  - Generating a mixture of Rb atoms, Rb_2^* Feshbach molecules and Rb_3^* trimers
  - Precisely measuring the lifetime of the first excited Efimov state, e.g. for $a = 700a_0$ the decay is $\tau \sim 120\ \mu s$)
- Drawback: This protocol couldn't distinguish the trimer and dimer energies

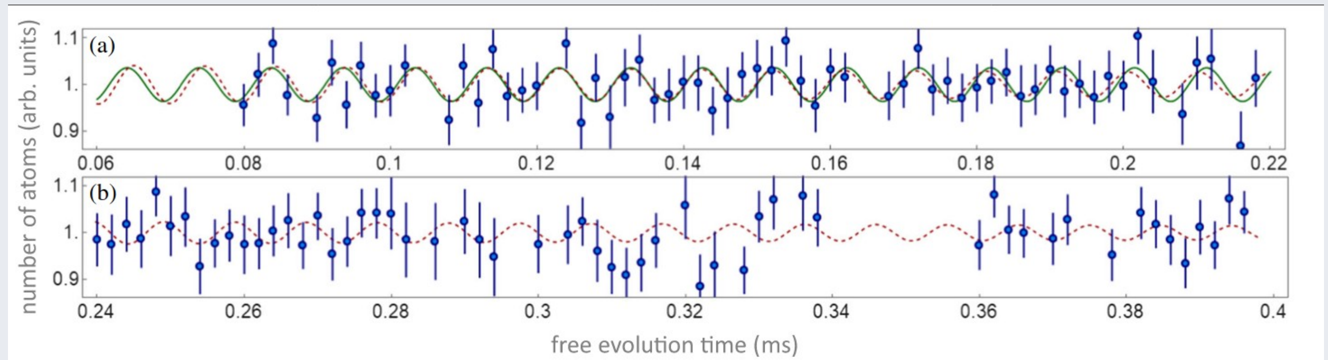
Motivation: Dynamics in few-body systems

Ramsey-type interferometry





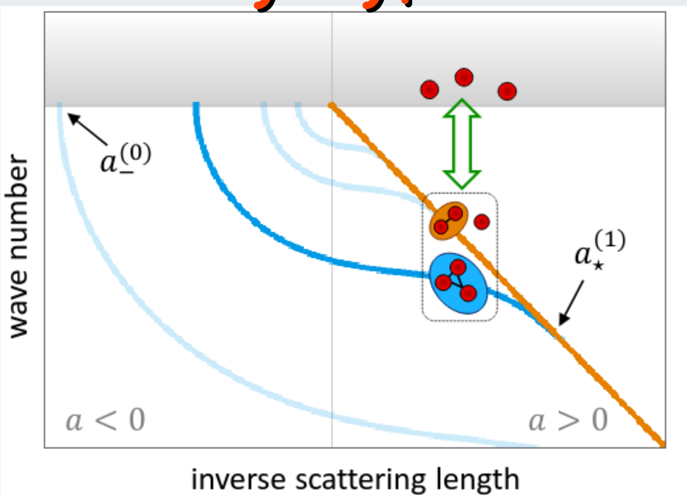
Yaakov Yudkin et al., PRL 122, 200402 (2019)

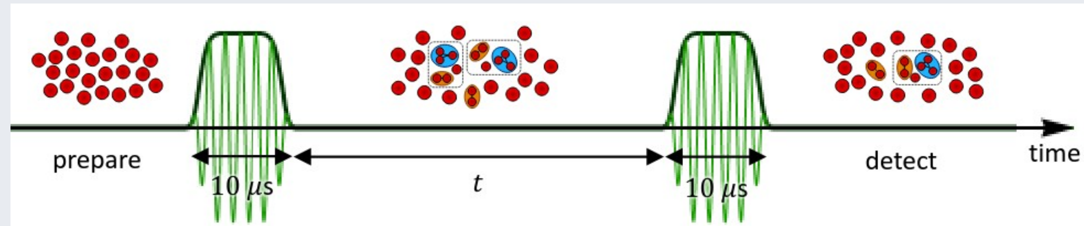


- A thermal gas of Li atoms: Ramsey-like double pulsed magnetic fields
- Generating a coherent superposition of Li_2^* Feshbach molecules and Li_3^* trimers
- Inteference fringes between Li_2^* and Li_3^* as function of the "dark time"
- Precisely measuring the energy difference between dimer and trimer, e.g. $\sim$ 100 kHz

Motivation: Dynamics in few-body systems

Ramsey-type interferometry





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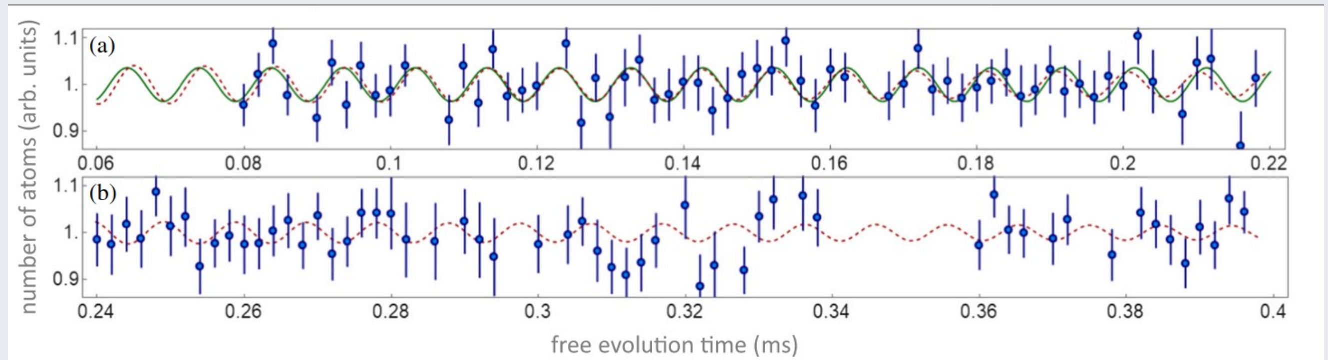


Open Questions:

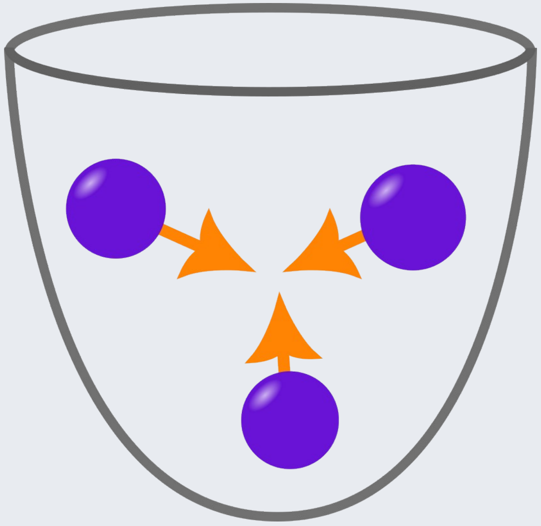
- How the coherence between the atom-dimer and trimers emerges in a thermal gas?
- The decay of the intereference is unusually long $\sim 300\ \mu s$, longer than the decay of trimers

Ramsey-type interferometry: Preliminaries

- Consider three equal mass ^{85}Rb atoms in a harmonic trap
  - Rb atoms are chosen since the lifetime of Efimov states is experimentally known
  - The trapping frequency is set by the gas density $\rightarrow$ same diluteness as in the experiment

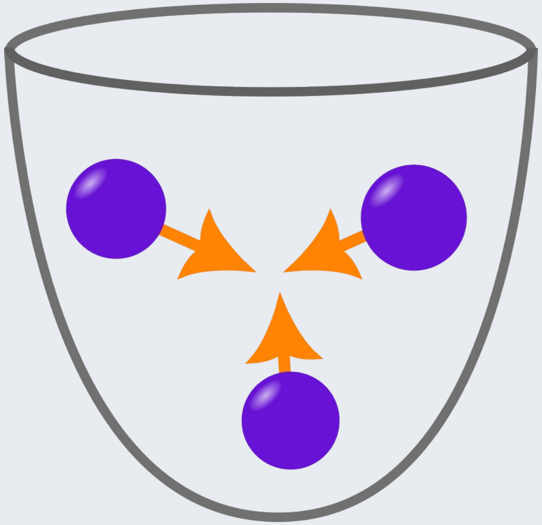
Catherine E. Klauss et al., PRL 119, 143401 (2017)

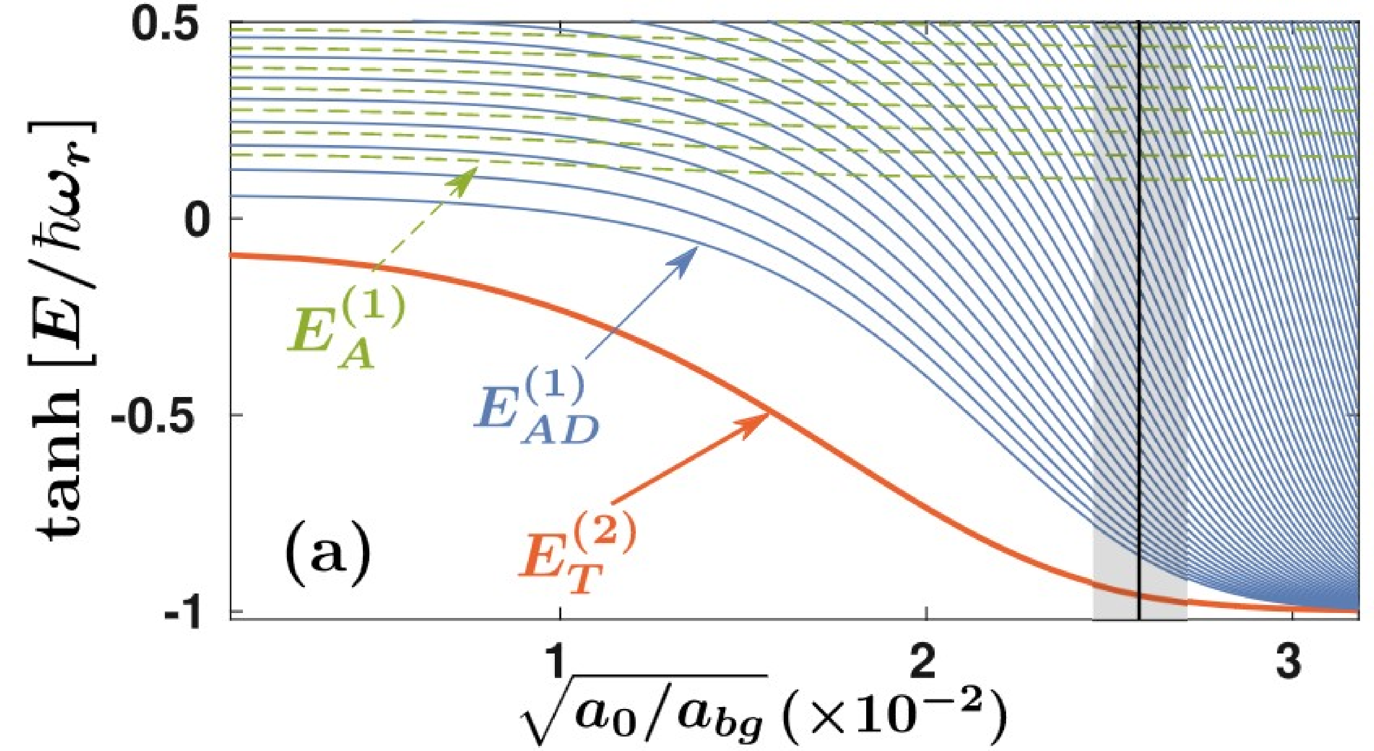
- The pairwise two-body potentials are modeled by zero-range interactions



Ramsey-type interferometry: Preliminaries

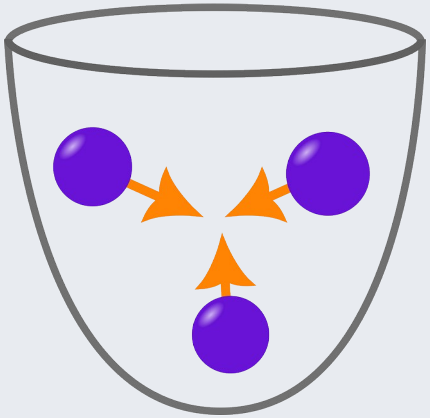
- Consider three equal mass ^{85}Rb atoms in a harmonic trap
- The three-body spectrum as a function of the scattering length

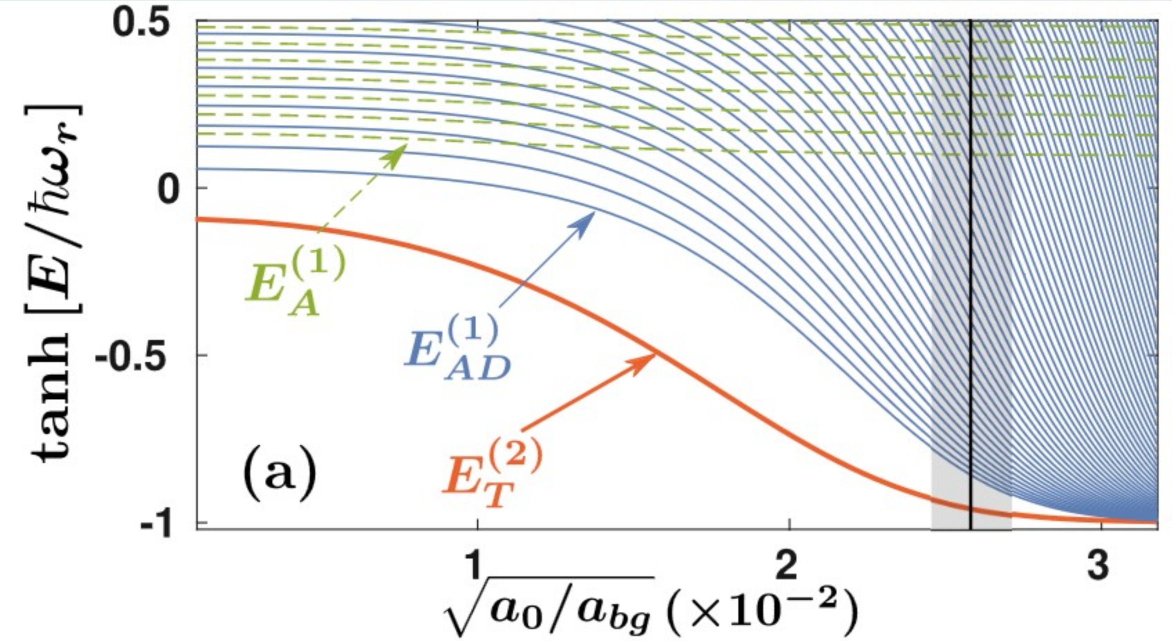




- Three types of states: Trap states, atom-dimer states, and trimer states

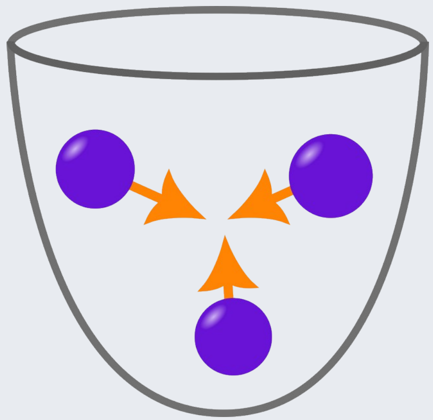
Ramsey-type interferometry: Preliminaries

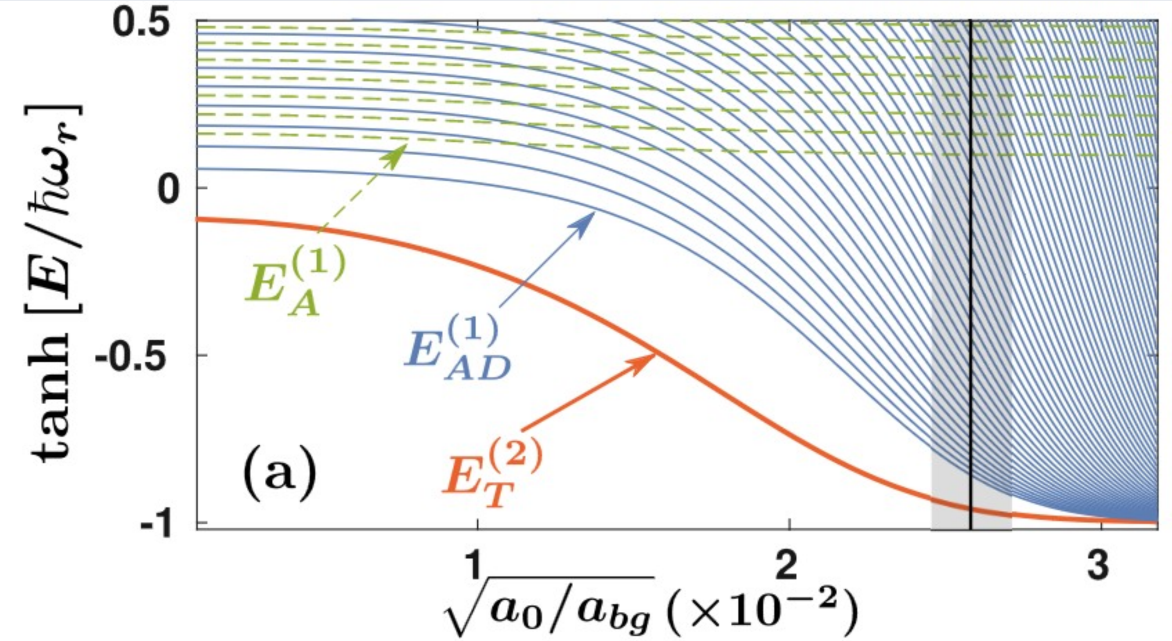




- Next consider a time-dependent scattering length $a(t)$:

Ramsey-type interferometry: Preliminaries





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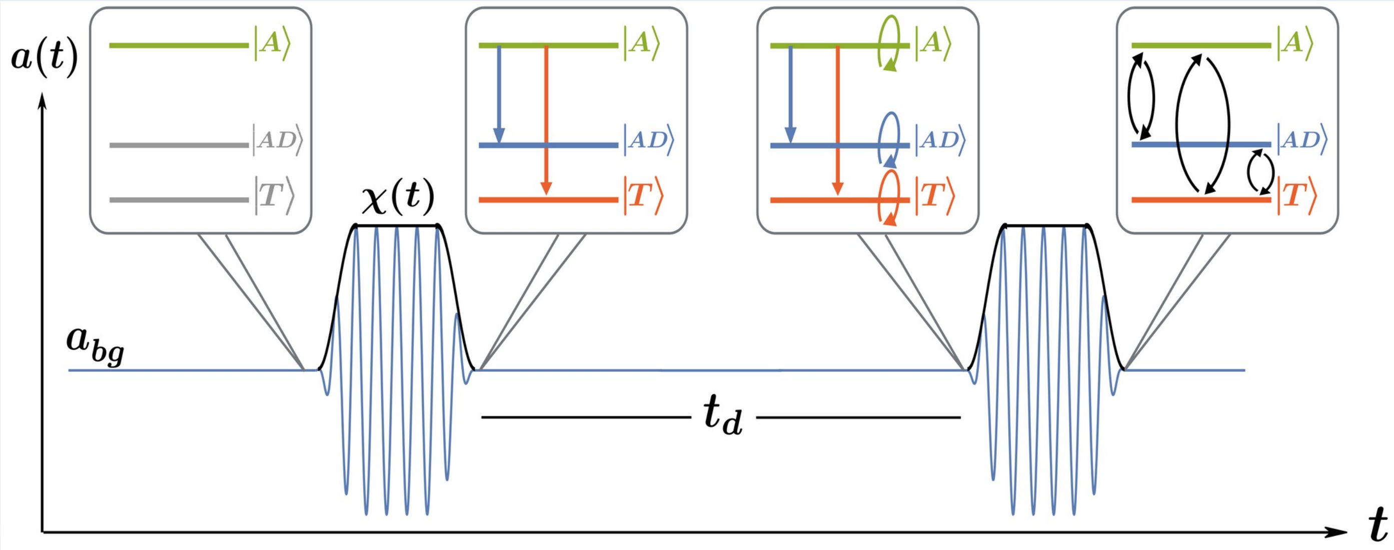


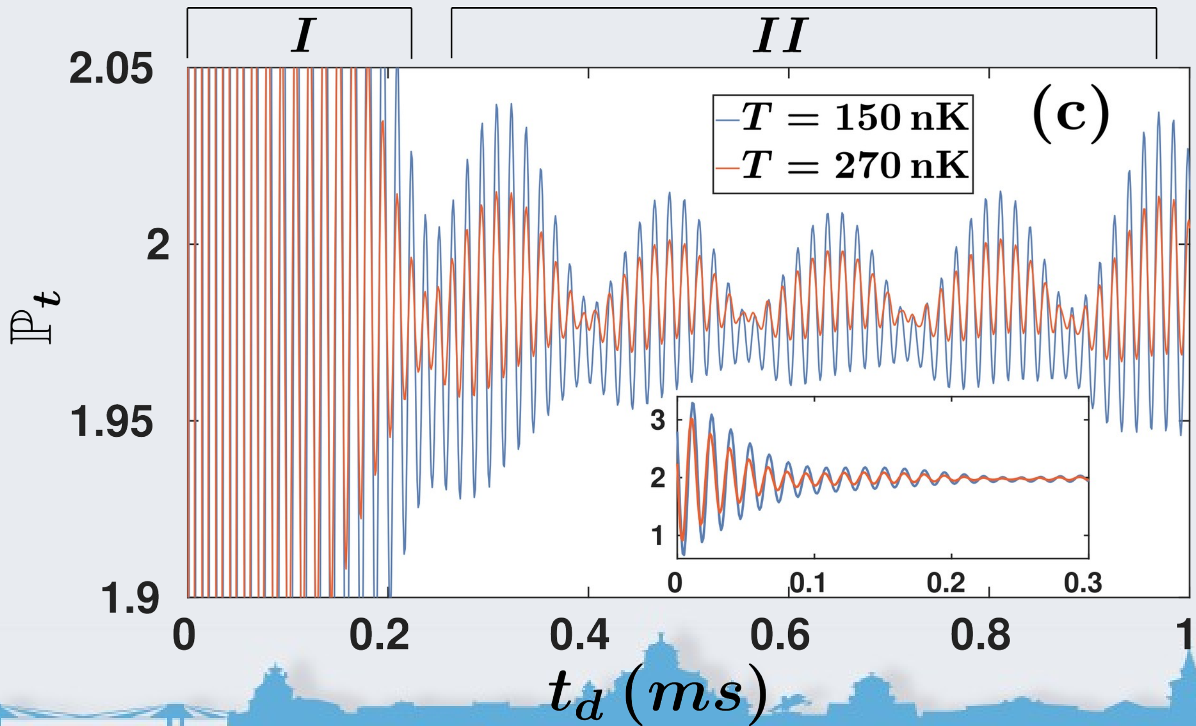
Ramsey-type interferometry: Results

- Quantity of interest - the population of trimers after both pulses
- Thermal gas → no preferable initial trap state→ averaging over Maxwell-Boltzmann distribution of initial states

$$\langle P_t(t_d)\rangle = N \sum_{n\in trap\ states} e^{-\frac{E_n}{k_B T}} |C_{n\to t}(t_d)|^2$$

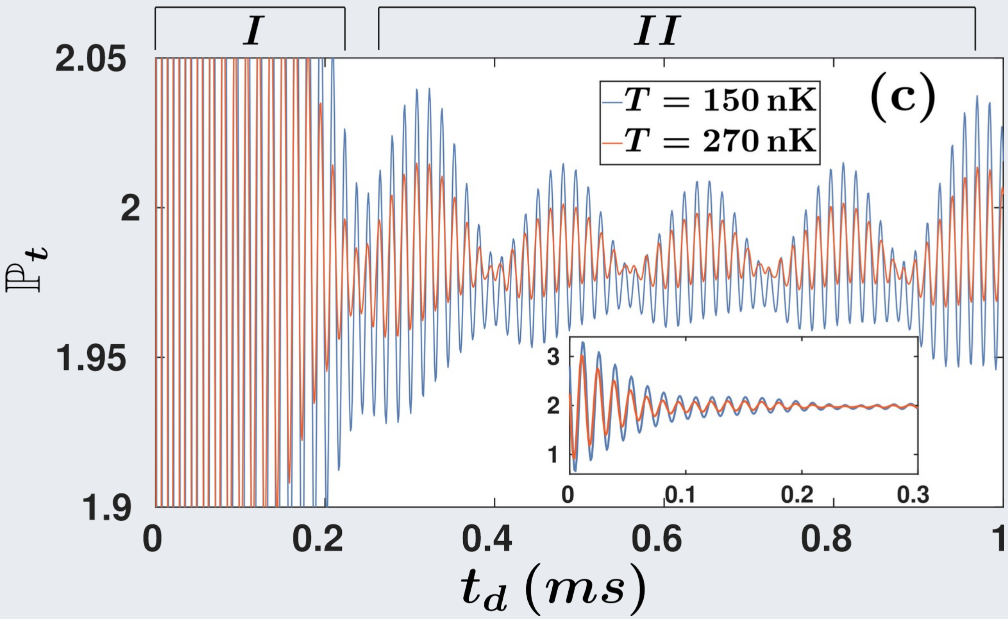
- Rescaling $\langle P_t(t_d)\rangle$ by the population after a single pulse, i.e. $\langle p_t\rangle$

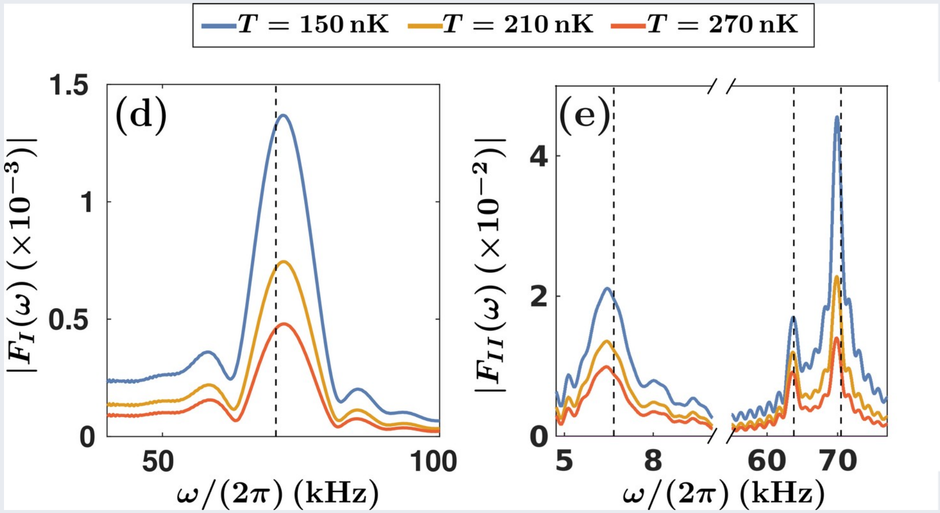
$$\langle \mathbb{P}_t(t_d)\rangle = \langle P_t(t_d)\rangle \,/\, \langle p_t\rangle$$



Ramsey-type interferometry: Results

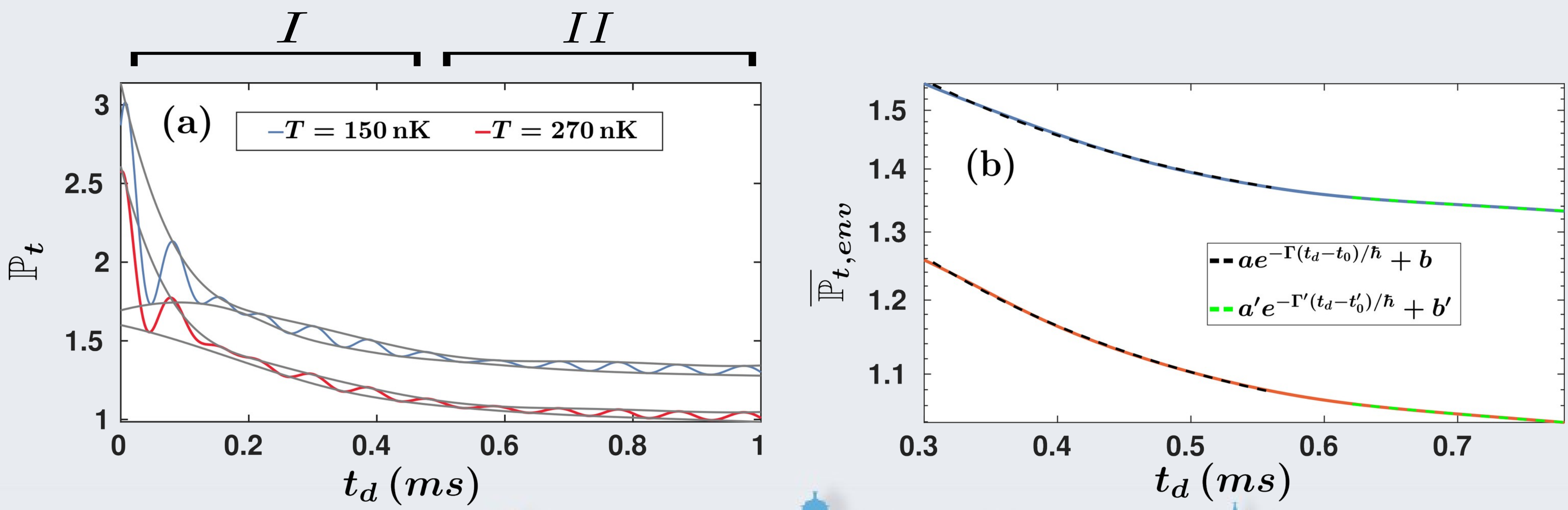
- Quantity of interest - the population of trimers after both pulses
- Robust interference in two regions:
  - Region I: Dominated by fast oscillations of frequency $\omega_1 = |E_t^{(2)} - E_a^{(1)}|/h$
  - Region II: Dominated by Slow oscillations of frequency $\omega_2 = |E_t^{(2)} - E_{ad}^{(1)}|/h$





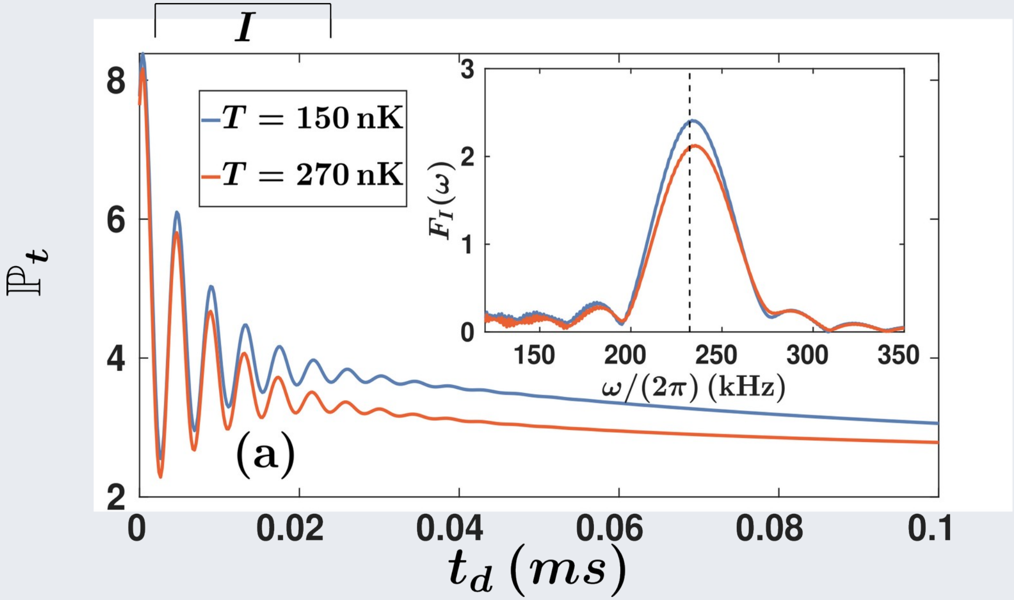
Decay of trimer states

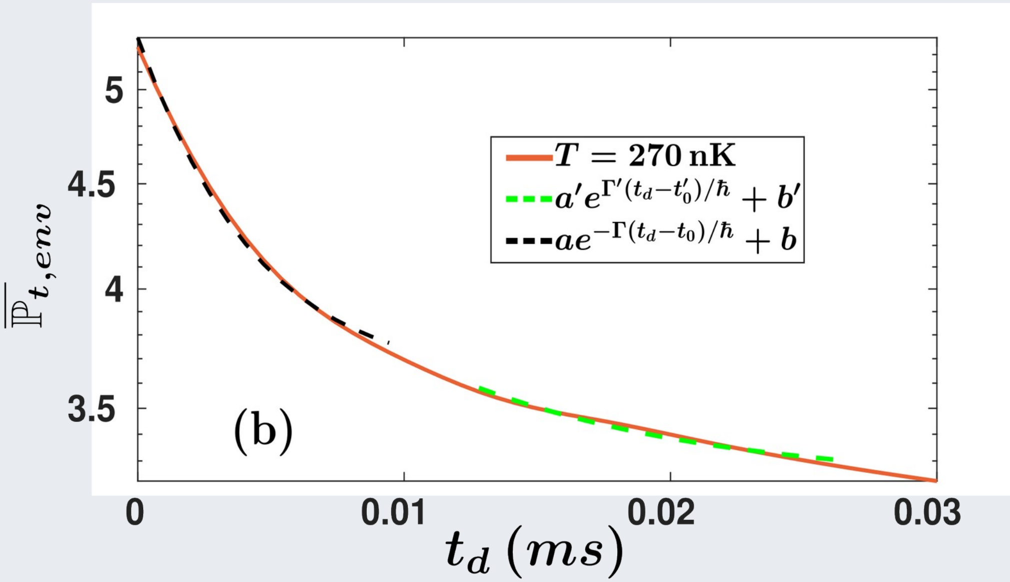
- Choosing a larger scattering length → provide relatively large decay times
- Taking into account the decay of trimers, i.e. $\tau_t = \hbar/\Gamma = 200\ \mu s$ for $a = 2000\ a_0$
- Decay of dimers is an order of magnitude longer than of trimers
- Two kind of decays:
  - Region I: Fast oscillations drop as $\sim \tau_t$
  - Region II: The atom-dimer + trimer oscillations decays as $2\tau_t$



Negative scattering lengths

- Fast oscillations only! $\rightarrow$ no atom-dimers present
- The decay in region I is equal to the decay of trimers





Conclusions

- Ramsey-type interferometry yields persistent interference fringes that survive the thermal average
- Exploiting such signals allows to measure the energy and lifetime of trimers at any scattering length
- The present theory can interpret the unusually long damping times in the atom-dimer+trimer experimental measurments in Y.Yudkin et al. PRL 122, 200402 (2019)

Interferometry of Efimov states in thermal gases by modulated magnetic fields arXiv:2306.01199 (accepted as PRR)

Ads

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Registration deadline 31st of October